A farm level approach to explore farm gross margin effects of soil organic carbon management

Glenk, K; Shrestha, S; Topp, CFE; Sanchez, B; Iglesias, A; Dibari, C; Merante, P

Published in:
Agricultural Systems

DOI:
10.1016/j.agsy.2016.11.002

First published: 22/11/2016

Document Version
Peer reviewed version

A farm level approach to explore farm gross margin effects of soil organic carbon management

Klaus Glenk[1,*], Shailesh Shrestha[1], Cairistiona F.E. Topp[2], Berta Sánchez[3], Ana Iglesias[3], Camilla Dibari[4] and Paolo Merante[4]

[1] Land Economy, Environment and Society Research Group, Scotland's Rural College (SRUC), Edinburgh, UK

[2] Crop and Soil Systems, Scotland's Rural College (SRUC), Edinburgh, UK

[3] Department of Agricultural Economics and Social Science, Universidad Politécnica de Madrid (UPM), Spain

[4] DISPAA Department of Agrifood Production and Environmental Sciences, University of Florence, Piazzale delle Cascine 18, 50144, Florence, Italy

* corresponding author. email: klaus.glenk@sruc.ac.uk

Abstract

This paper investigates farm gross margin effects of management measures aimed at enhancing soil organic carbon (SOC) stocks to maintain soil fertility while providing important ecosystem services. An optimising farm level model, ScotFarm, is used to investigate the farm gross margin effects of selected SOC management measures for arable farms in Scotland (UK) and Aragon (Spain). The sensitivity of model results to effects on crop yields and costs of production is tested for each measure. The results suggest that considerable regional differences in the financial viability of SOC measures exist. Tillage management is the only measure with positive effects on farm gross margins of Scottish farms at baseline levels of yield effects and input costs. In the case of farms in Aragon, Spain, fertiliser management, crop rotations (with legumes) and tillage management (in later years) show improvements in gross margins. Residue management is estimated to have a negative effect on farm gross margins for both Scottish and Spanish crop farms. Results of the sensitivity analysis indicate that effects of SOC management on farm gross margins are more sensitive to a change in crop yields than to changes in input costs. The findings point to further research needs with respect to the trade-offs between yield effects and changes in input costs arising from the adoption of SOC management measures, and have implications for agricultural policy design aimed at enhancing SOC stocks under a changing climate.

Key words:

soil organic carbon, soil management, farm level modelling, arable farming, trade-offs, profitability

Highlights:

- A farm level model is used to assess effects of different SOC management practices
- Analysis of the trade-offs between effects on yield and input costs on farm gross margins (GM)
- GM effects: more sensitive to crop yield changes than to changes in input costs
- Maximum positive effect on GM greater for Aragon (Spain) compared to Scotland (UK)
- In total three SOC measures are found to be relatively robust to assumptions made

1. Introduction

The stocks of Soil Organic Carbon (SOC) interact in a complex manner with soil properties and functions that ultimately affects the provision of ecosystem services (Robinson et al. 2013; Dominati et al. 2010). Management of SOC in arable agricultural systems can affect the productive capacity of land as a final ecosystem service by improving the growth conditions for crops and therefore yields, and by increasing nutrient use efficiency that may affect the amount of fertiliser input required for optimal plant growth (e.g., Luxhøi et al. 2007; Pan et al. 2010). These effects are related to intermediate services that are affected by soil organic matter stocks and flows, including the provision of plant available nutrients, the control of erosion/loss of topsoil, the provision of a platform for (root) growth, the provision of a moisture regime that is suitable for plant growth, levels of biological diversity influencing pest/disease control, and the provision of a habitat for soil-based pollinators (Glenk et al. 2013). Additionally, management of SOC has been associated with a wide range of potentially beneficial (co-)effects, notably the potential to contribute to climate change mitigation via soil-based carbon sequestration, to help improve water quality at catchment level, and to enhance sub-soil and aboveground biodiversity (Freibauer et al. 2004; Feng and Kling 2005; Smith et al. 2007a; Glenk and Colombo 2011).

Despite an increasing policy interest in increasing SOC stocks (EC 2011), there is a lack of evidence on the magnitude of private benefits of changes to SOC management to farmers. Such evidence is needed, however, to provide meaningful guidance to farmers and to inform considerations of policy support aimed at enhancing the uptake of SOC management measures. This paper contributes to filling this evidence gap. The objective of this study is to investigate the effects on farm gross margins of adopting suitable SOC management measures for a number of representative arable farms in two EU-regions (Scotland, UK; Aragon, Spain).

Additionally, this study aims at assessing the robustness of farm gross margin effects to changes in effects on nutrient availability and yield. Nutrient availability and yield effects are of great relevance in the context of moving to sustainable agricultural systems that provide food security in the mid- and long term (Kahiluoto et al. 2014), where food demand is expected to increase and substitution of organic fertilisers through inorganic ones may become increasingly challenging (Cordell et al. 2009).

Effects of SOC management on crop production are climate, soil and crop specific (Sánchez et al. 2016a), and therefore differ between the investigated SOC management measures, which include, for example, cover crops, residue management, and zero and reduced tillage. Within the SOC management measures and under given environmental conditions there is considerable uncertainty regarding their effect on nutrient availability, yield and other effects on variable costs of farming including pest control and changes in farming operations, which are highly dependent on spatial context and farm characteristics (Morris et al. 2010; Rickson et al. 2010). This paper uses plausible ranges of key parameters regarding the effects on nutrient availability, yield effects, pest control and farming operations derived from expert knowledge and guided by available literature. Data on plausible ranges of effects then enter a sensitivity analysis using an optimising farm level model (ScotFarm) to reveal the robustness of SOC management measures to changes in input costs and yield effects. High levels of variability in farm gross margin effects can act as a barrier to uptake especially by risk averse farmers.

2. Methodology

2.1 Model structure

The profit maximising dynamic farm level model ScotFarm (Shrestha et. al. 2014) is used to investigate farm gross margin effects of different SOC management measures for representative crop farms in each of the two EU study regions (Scotland, UK; Aragon, Spain). The model follows the classic linear programming structure as provided in equation (1) below.

$$\text{Max } z = (p - c) * x + SFP \text{ subject to } A * x \leq R \text{ and } x \geq 0, \quad (1)$$

where z is the farm gross margin, x is the quantity of each crop produced on farm per hectare, p is the revenue collected from activity x, c are the costs incurred to produce activity x, SFP is the farm payment, A is an input-output coefficient of activity x, and R is a limiting farm resource.

The model is based on farming system analysis (Fresco 1988; Keating and McCown 2001), where all existing farm activities and interactions between farm structure, management, activities and management are taken into account. The model structure is represented in Figure 1 below.

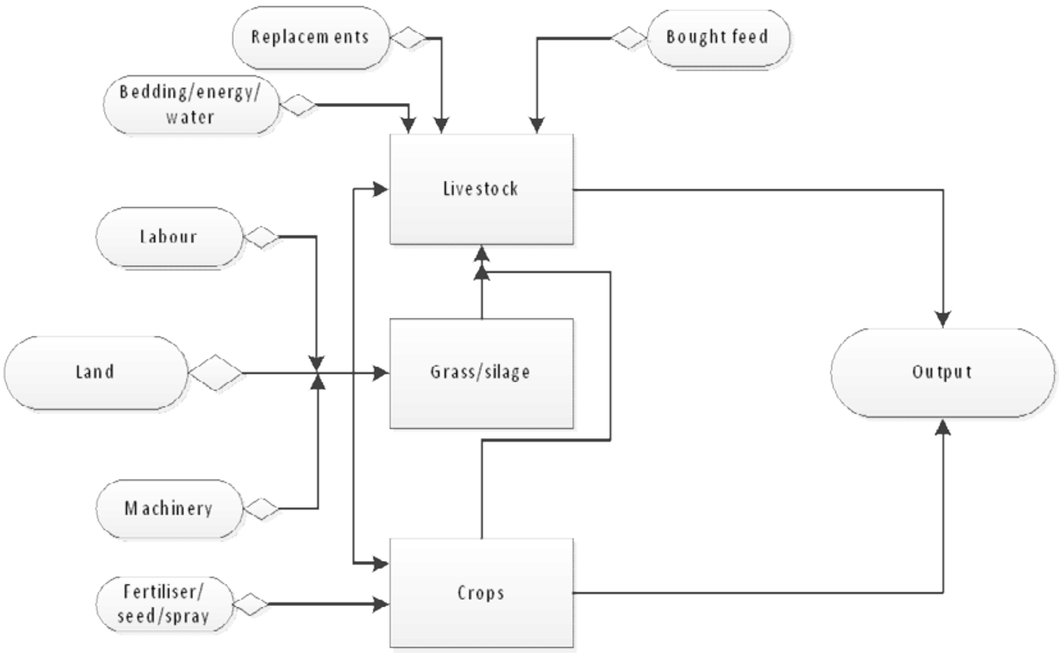

Figure 1. A schematic diagram of ScotFarm

It is assumed that farmers are profit oriented and maximise farm gross margins within a set of limiting farm resources. The farm gross margin is comprised of the accumulated revenue from the final products of different farm activities and from farm subsidy payments, minus the cost incurred for inputs for the farming activities. ScotFarm is an optimising model, hence it should be noted that the results provided by the model are based on achieving all farm activities and farm management to the optimal level.

There is an emphasis on the crop component of the model in this study. The model encompasses crop production that is limited within fixed available land (Equation 2).

$$ALAND \geq \sum_{c=1}^{n} ACROP_{\mathrm{c}} \qquad \forall f, y \tag{2}$$

where ALAND is the total area of arable land available for farm *f* in year *y* and ACROP is the land area under crop *c*.

All major crops in each region are available for selection in the model. The area of total farm land is fixed (ALAND), but the model re-allocates arable land under each of the crops from year to year. The area under each crop is assumed to be at least 50% of the area under the same crop in the previous year to facilitate a smooth transition in change in crop activity. The model selects the most profitable crop based on revenues collected, which is determined by yield and the price of the crop, and the costs of production incurred (Equation 3).

$$C\rho = \sum_{c=1}^{n} ACROP_c * (YIELD_c * \; price_c - costs_c) \tag{3}$$

where $C\rho$ = crop gross margins, $ACROP$ = land cover, $YIELD_c$ = crop yield and $costs_c$ = costs of production (fertiliser use, sprays, seeds and machinery costs) for each crop c.

The model is used to analyse the effect on farm gross margins of changes in crop yields and costs of production for a range of SOC management measures and representative farm types in each of two study regions. The model adjusts farming activities based on the changes in crop yields and costs of production to optimise the farm gross margin when SOC management measures are available.

All the activities are constrained by labour availability to comply with labour requirements. The labour requirement for each activity is based on literature and expert knowledge. Total labour available on farm is derived from existing information on family labour units available in farm level data. Family labour is assumed to be skilled labour, providing up to 2,200 hours per labour unit each year. Apart from family labour, farm activities also use contract costs (labour and machinery), which are crop specific and included in the variable costs of crop production. The model assumes contractors are available all year round and hence seasonal variability of the labour requirement is not considered in the model.

Grass and livestock production are additionally considered for Scotland (UK), because many Scottish crop farms also have sheep/beef animals and use some of the crops produced to feed animals. Grassland can be transformed to arable land and vice versa based on the profitability of each of the production system. For livestock feed, besides grazing and grass silage, each farm types has a minimum level of concentrate fed to the animals on farms (based on existing data). This requirement of concentrate feed is first fulfilled by the cereal crop produced on farm and then if required more brought in from the market. Farms in Aragon (Spain) primarily focus on arable production but may also keep pigs. There is no direct link between pig production and arable production, because farmers usually feed their animals with concentrate obtained from the market. Therefore, a pig component was not developed for modelling farms in Aragon.

The model is run over a period of 21 years. The input data for the first year is based on available farm level data. For subsequent years, farm activities are based on the activities in the previous year and costs, prices and availability of farm resources for that particular year. For example, for the livestock component the number of year-old beef animals depends on the number of calves born and calves sold in the previous year. The area under each crop in a particular year is based on the number of livestock in that year (if it is a mixed farm) and the area under that crop in the previous year. Changes in costs and prices for each year are determined using price indices taken from a partial equilibrium model FAPRI (AFBINI, 2012; Binfiled et al. 2015). Model results are obtained for each year but results for the first and last three years are discarded to minimise initial and terminal effects of linear programming (Ahmad 1997; Shrestha 2004). The results for the remaining 15 years are presented in 5-yearly averaged figures.

The model was run under a ‘baseline’ scenario for each region and farm type, where crop yields and input costs are based on farm level data, and a number of soil organic carbon management (SOC) scenarios based on the specified SOC management measures. To infer the effect of the SOC management measures on farm gross margins, the model results of the SOC management scenarios are compared to results of the baseline scenario. The input parameters used for the changes in crop yields and input costs under the SOC management measures are based on literature and observed data if available, and adjusted using expert knowledge to allow for estimates that better reflect the heterogeneity in environmental condition in the case study regions. Details on input parameters are provided in Section 2.5.

To analyse the effects of SOC management measures on farm gross margins, three sets of parameters for changes in yield effects and input costs were employed that represent the plausible range that each can take across the range of farms within the two regions. The first set of parameters reflects typical farming conditions (**Y** for crop yield and **C** for input costs). The remaining two sets of parameters will be used to investigate the sensitivity of farm gross margin effects to all four combinations of lower bound ($\mathbf{Y_{min}}$ and $\mathbf{C_{min}}$) and the upper bound ($\mathbf{Y_{max}}$ and $\mathbf{C_{max}}$) values of the plausible range.

The results across the four resulting cases demonstrates the relative trade-offs between yield effects and changes in input costs associated with each management measure. This provides important insights into the robustness of SOC management measures to result in positive changes in farm gross margins.

2.2 Study regions

As part of the EU FP7 project SmartSOIL[1], case study regions have been selected to support the collation of data in different bio-geographic and social-economic agricultural areas, to develop scenarios for different farming systems and regions in

[1] For details see http://smartsoil.eu/

Europe and to engage and consult with stakeholders at local and regional level (farmers, farm advisory and extension services, policy makers etc.). The regions included in this study are Scotland, UK and Aragon, Spain (Figure 2). The two regions reflect different agro-ecological conditions and allow a first insight into the regional heterogeneity of in the potential of SOC management measures across Europe. There is an increasing interest in management practices that will improve the soil carbon (Scottish Government, 2005; Sánchez et al. 2016a). A brief overview of the study regions are provided below.

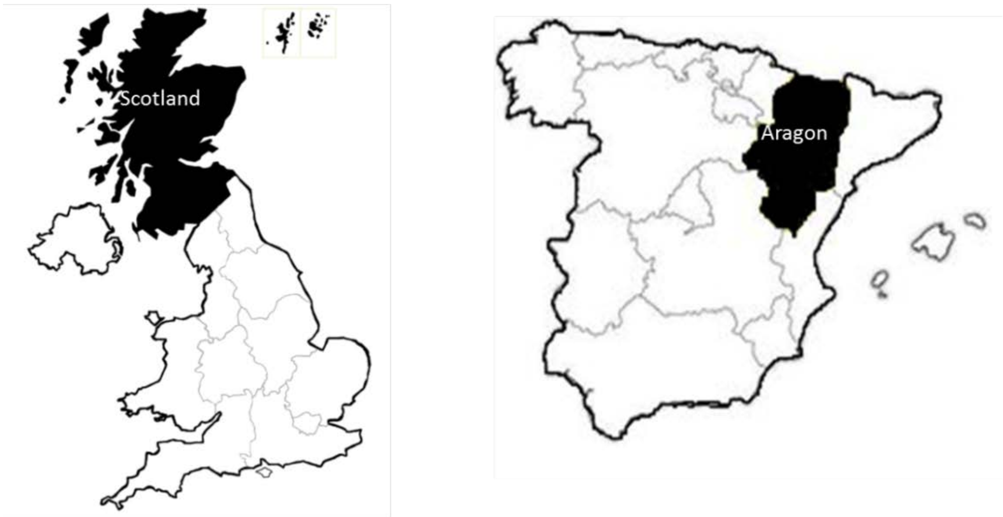

Figure 2. Study region Scotland, UK and Aragon, Spain

2.2.1 Scotland

Arable farms in Scotland are mostly concentrated in the East covering around 0.6 million hectare of land. Scotland has a maritime climate, and is influenced by the Atlantic gulf stream (the average annual rainfall for the arable area is between 400-900 mm, and the mean average temperature is between 6 ºC to 7 ºC). As shown in Table 1, the average arable land area for these farms is 132 ha. These farms also have 64 ha of grassland on average. The main crops produced on farms are winter wheat, spring barley, spring oats and break crops, for example winter oilseed rape. Potatoes and other horticultural crops are not included in the study as they are not targeted by the SOC management measures considered in the study. Agricultural management is largely based on conventional tillage and the use of fertilisers and pesticides.

Table 1. Characteristics of arable farming in Scotland (UK) and Aragon (Spain)

Region	Arable area (ha)	Grass area (ha)	Family labour (Man units)	Single Farm Payment (€)
Scotland, UK[a]	132	64	2.00	59,324
Aragon, Spain[b]	147	155	0.00	28,729

Source: [a] FAS (2012); [b] INE (2009)

2.2.2 Aragon

In Aragon, the fourth largest agricultural region in Spain, about one fourth of the land is dedicated to agricultural activities. As shown in Table 1, crop farms have 147 ha of arable land on average and grow cereal crops (wheat and barley), maize and alfalfa under irrigated and rain fed systems. Some of the farms also have land under almond, vineyard and olive production under a rain-fed system. The above mentioned crops account for 75% of the total cropland area of the region and the farms receive less than half of the single farm payments received by their counterparts in Scotland. There is also a considerable land area under grass on average.

Aragón is a semiarid region located in north-eastern Spain where the climate is Mediterranean with continental influence (i.e., mean annual temperatures about 7 ºC to 15 ºC and mean annual precipitation from 300 to 800 mm). Agricultural management is mostly conventional based on intensive tillage, high fertilization rates (mineral and organic), frequent use of herbicides to control weeds and monocultures (Álvaro-Fuentes et al. 2011; Sánchez et al. 2016b).

2.3 Farm level data

The modelling work required detailed farm level data for each of the study regions. The data was acquired from the Farm Accounting Survey (FAS) data for Scotland (FAS, 2012) and Aragon Census Data for Aragon, Spain (INE, 2009). The Scottish FAS data has been found to represent farming activity well with respect to geographical distribution and level of production (Scottish Government, 2013). For the Aragon region, INE (2009) provides the most accurate and complete data for the specific inputs required for the model. These two datasets provided farm level data for 135 crop farms in Scotland and 105 farms in Aragon. Data included information on farm characteristics including land area under different crops, labour availability, farm subsidy payments, crop revenues and costs of production. The crop farms were clustered into three types (large, medium and small) based on different farm variables such as farm size and farm gross margins using k-means clustering. Farm characteristics in each of the types are averaged and used in the model as the "representative" arable farm for each type. The farm characteristics relevant to the model include land use shares, average crop yields, crop gross margins (derived from revenues collected minus costs of production) as well as feed crops in Scottish farm groups.

2.3.1 Scotland

For Scotland, the cluster analysis was based on farm area, family labour and farm payments and resulted in three representative farm types Crop Large, Crop Medium and Crop Small with 67%, 26% and 7% of farms in the data allocated to the three clusters. Farm characteristics of each of the types are shown in Table 2. There are four main crops produced on the farm types, with differing average land allocations for the four crops in each of the farm types (Table 2).

Table 2. Farm characteristics (Scotland)

Farm type (% of farms in data in parentheses)	Grass-land (ha)	Rough grazing (ha)	Arable land (ha)				Family labour (Man Units)	Single Farm Payments (£)
			Wheat	Barley	Oats	Oilseed		
Crop Large (67%)	178.3	0	104.4	106.1	0	16	7.5	77,258
Crop Medium (26%)	86.3	6.9	50.3	130.7	7.4	23.1	2.7	80,350
Crop Small (7%)	46.6	5.1	17.6	61.9	3.6	4.2	1.5	34,023

Source: FAS (2012)

2.3.2 Aragon

In the Aragon region of Spain, crop farms were separated in three farm types based on agriculture area and number of farms. The farm types are (similar to Scottish farm types): Crop Large (11% of farms in the data), Crop Medium (45%) and Crop Small (44%). The characteristics of farms in each of the farm types, and the land allocated to crops on farms in the different types, are presented in Table 3.

Table 3. Farm characteristics (Aragon, Spain)

Farm type (% of farms in data in parentheses)	Grass-land (ha)	Rough grazing (ha)	Arable land (ha)											Single farm payments (€)
			Total	WR	WI	BR	BI	M	A	AM	V	O	F	
Crop Large (11%)	245.4	302.1	254.5	30.3	8.3	49.0	11.2	10.3	10.6	8.5	4.2	5.2	71.2	25,451
Crop Medium (45%)	209.8	246.3	172.4	20.5	5.6	33.2	7.6	7.0	7.2	5.8	2.8	3.5	48.2	17,245
Crop Small (44%)	10.9	10.2	12.8	1.5	0.4	2.5	0.6	0.5	0.5	0.4	0.2	0.3	3.6	1,278

Source: INE (2009)
Note: WR: Wheat (rainfed); WI: Wheat (irrigated); BR: Barley (rainfed); BI: Barley (irrigated); M: Maize; A: Alfalfa; AM: Almond; V: Vineyard; O: Olives; F: Fallow

2.4 SOC management measures

The suite of SOC management measures considered for this study is based on expert opinion about the measures' feasibility in each case study region, and draws on previous work on cost-effectiveness of SOC management and barriers for uptake in the case study regions (McVittie et al. 2014; Sánchez et al. 2016a,b). Feasible SOC management measures and crop combinations for each of the case study regions were then selected based on the observed cropping activities in each region. The selected SOC management measures can be characterized as follows, based on Wösten and Kuikman (2014)[2] and Flynn et al. (2007), with specific reference to potential processes related to carbon sequestration and GHG emission reduction in order to derive upper and lower bounds for the effect these measures are expected to have on SOC (Table 4).

2.4.1 Cover crops (Scotland, Aragon)

This is the provision of a temporary vegetative cover between agricultural crops, which is then ploughed into the soil. The vegetative cover can include legumes. These cover crops very efficiently add carbon to soils (Poeplau and Don 2015) and non-legume based cover crops may also extract plant-available nitrogen (N) unused by the preceding crop, and thereby reducing leaching and therefore indirect nitrous oxide (N_2O) emissions (Paustian et al. 2016). In the case of legume-based cover crops, the amount of fertiliser N that needs to be added can be reduced (St Luce et al. 2016). Seed mixes with legumes (e.g., clover) have higher cost and differ in fertiliser requirements, but may result in greater SOC gains and yield effects than non-legume seed mixes, although a recent meta-analysis does not support this finding (Poeplau and Don 2015). Nevertheless, in water limited regions, cover crops may reduce yield (Blanco-Canqui et

[2] see Smith et al. (2007b) for a detailed description of agricultural SOC management measures.

al., 2015). For Scotland, as the opportunity cost (see McVittie et al., 2014) of switching between winter and spring sown crops has not been considered in the model, only spring barley and spring oats are considered to be affected under this scenario, which comprise 60%-70% of the annual cereal hectare in Scotland.

2.4.2 Zero tillage (Scotland, Aragon)

Advances in weed control methods and farm machinery now allow many crops to be grown without tillage (zero tillage or no till). In general, tillage promotes decomposition, reducing soil carbon (C) stores and increasing emissions of GHGs (Guardia et al. 2016), through increased aeration, crop residue incorporation into soil, physical breakdown of residues, and disruption of aggregates protecting soil organic matter. Therefore, zero tillage often results in SOC gains (Whitmore et al., 2015; Paustian et al. 2016), although this may be the result of a change in the distribution of the soil carbon through the profile (Powlson et al. 2014). Nevertheless, zero tillage practices enhance the soil quality in terms of its microbial biomass and enzyme activity (Melero et al. 2011, Mangalassery et al. 2015). The enhanced soil carbon in the top soil and the increased soil quality is likely to have beneficial effects on production in the long-term, although there is a risk of yield reduction in the short to medium term (Sun et al., 2011).

2.4.3 Reduced tillage (Scotland)

Reduced tillage can take many forms including ridge tillage, shallow ploughing and rotovation, or scarification of the soil surface. All cause less soil disturbance than conventional deep tillage with a mouldboard plough. Reduced tillage decreases decomposition and can enhance the soil quality (Melero et al. 2009), and increase the

SOC stock (Paustian et al. 2016). However, in the short to medium term, yields can be reduced compared to conventional ploughing (Sun et al, 2011).

2.4.4 Residue management (Scotland, Aragon)

Residue incorporation, where stubble, straw or other crop debris is left on the field, and then incorporated when the field is tilled, is used in some areas for water conservation, but also enhances carbon returns to the soil, thereby encouraging carbon sequestration. However, incorporation can increase N_2O emissions and therefore net benefits in terms of climate mitigation may be highest when residues with high N content are removed. The contribution of crop residues to soil organic matter differs per crop, and is dependent on the carbon content (Justes et al. 2009). Crops with lower C:N ratios tend to results in more of the N being mineralised and hence available to the following crop (Justes et al. 2009). For the context of this paper, tillage operations are not assumed to change and will thus remain conventional for this measure.

2.4.5 Fertilisation with animal manures (Aragon)

Incorporating animal manures to arable land is expected to encourage carbon sequestration, because it increases organic carbon stores and enhances carbon return to the soil. However, an increase in N_2O emissions can be associated with the manure management undertaken (Freibauer et al. 2004). Manure management may imply large infrastructure requirements in terms of improved storage and handling, and add extra cost due to additional demand for labour and fuel (Smith et al. 2007a). In Spain, for example, the low availability of manure on farms and the restrictive legislative requirements for manure management, treatment and transportation (EU Nitrates Directive 91/676/EEC) may limit its use by many farmers (Sánchez et al. 2016b).

2.4.6 Optimised fertiliser application (Aragon)

Being optimised and therefore more efficient in fertiliser application (at the right time of the crop growth and under the most optimal weather and soil conditions) is associated with lower fertiliser rates. Further, the optimised fertilisation stimulates the plant growth, plant and root biomass and the microbial activity, having a direct impact on SOC (López-Bellido et al. 2010). Particularly, N fertilisation should be managed by site-specific assessment of soil N availability to be able to mitigate atmospheric CO_2 enrichment (Khan et al. 2007). In Mediterranean regions, N fertilisation was found to have a long term effect on SOC dynamics depending to the management applied and the soil water content (Morell et al. 2011a; Álvaro-Fuentes et al. 2012). Nevertheless, optimising fertiliser application is unlikely to have a negative effect on SOC.

2.4.7 Crop rotation with legumes (Aragon)

Using crop rotations which include legumes increases soil carbon stores and requires reduced fertiliser use, thereby reducing N_2O emissions. Inclusion of legumes in a cereal crop rotation has a positive effect on the content and the quality of SOC. In Spain, McVittie et al. (2014) report that this was not considered an appropriate practice in arid areas with precipitation below 350 mm year^{-1}. Crop rotations have shown a positive effect over time on SOC sequestration and content in rainfed Mediterranean due to C additions as plant and root biomass, and due to better soil structure (López-Bellido et al. 2010).

2.5 Effects of SOC measures

2.5.1 Effects on SOC content

The main policy interest in SOC management measures is to increase SOC stocks. While not relevant as a model input, SOC accumulation rates for the measures identified for the case study regions are listed in Table 4 to provide context for an appraisal of their effectiveness in achieving increases in SOC stocks. Reported values are based on expert knowledge guided by the literature quoted in section 2.4 and by papers that synthesise the effects of the measures on soil carbon (listed in Table 4). The 'best estimate' refers to typical rates whereas the lower and upper bound values (Min and Max) reflect the uncertainty regarding the assumptions behind SOC accumulation estimates.

Table 4. SOC accumulation rates for measures in kgC ha^{-1} yr^{-1}

SOC measures		Best estimate	Lower bound	Upper bound	Relevant synthesis papers
Cover crops (legume)		400	0	800	Smith et al (2008); Lal and Bruce 1999; Steenwerth and Belina 2008; Nieto et al. 2013; Ogle et al, 2005; Poeplau and Don 2015
Cover crops (non-legume)		200	0	400	
Zero tillage		0	-100	100	Smith et al (1997, 1998); Freibauer et al (2004); West and Post (2002); Sun et al. (2011); Troccoli et al (2015); Whitmore et al (2015)
Reduced tillage		0	-100	100	Ball et al. (1994); Arrouays et al (2002); Bhogal et al (2007); Sun et al. (2011); Powlson et al 2012
Residue management	Years 0-20	400	0	800	Powlson et al (2008); Freibauer et al (2004); Powlson et al (2012); Troccoli et al. (2015) Pituello et al. (2015)
	Years 21-25	300	0	600	
Fertilisation with animal manures		200	0	400	Paustian et al. 1997; Smith et al. 1997; Follet 2001; Smith et al. 2008; Freibauer et al. 2004; Oberholzer et al. (2014); Whitmore et al (2015)
Optimised fertiliser application		0	0	100	Lal and Bruce 1999; Follet 2001; Snyder et al. 2009
Crop rotations (with legumes)		400	0	800	Lal and Bruce 1999; Follet 2001; West and Post 2002; Lal 2004

2.5.2 Effects on yield, nutrient availability and elements of variable costs

2.5.2.1 *Yield*

Table 5 reports average yield for crops in the two case study regions. The values define yield in the baseline scenario (no SOC management measures) of the model. Yield changes as result of SOC management measures are then included in the model relative to these baseline yield values.

Table 5. Baseline yields for crops in Scotland (UK) and Aragon (Spain)

Crops	Average yields (t/ha)	
	Scotland[a]	Aragon[b]
Winter wheat	8.5	-
Spring barley	6.5	-
Spring oats	5.7	-
Wheat (rainfed)	-	2
Wheat (irrigated)	-	4
Barley (rainfed)	-	2.3
Barley (irrigated)	-	3.7
Maize(irrigated)	-	9.5
Alfalfa (irrigated)	-	15.2
Almond (rainfed)	-	0.5
Vineyard (rainfed)	-	3.3
Olives (rainfed)	-	0.8

Source: [a]SAC Farm Management Handbook 2012/13 (SAC 2012); [b] Spanish Agricultural Census 1999/2011

Table 6 reports the plausible range of changes in crop yields for the SOC management measures considered for the case study regions. Changes in yield show a similar pattern for the SOC management measures common to both case study regions. However, cover crop effects are more pronounced in Aragon (see Gabriel and Quemada 2011; Blanco-Canqui et al 2015) and tillage is assumed to have a greater effect on yield after the initial years (see Table 6 for references); however there is an increased risk of the yield being reduced in wet seasons (Soane et al. 2012).

Table 6. Percentage (%) change in yield under different SOC measures in t C ha^{-1}

		Scotland			Aragon			References
SOC measures	Years	Mean	Min	Max	Mean	Min	Max	
Cover crops (legume)		+5	+-0	+20	+10	-10	+30	Gabriel and Quemada (2011); Li et al. (2015); Blanco-Canqui et al. (2015)
Cover crops (non-legume)		+-0	-5	+10	+5	-5	+10	Gabriel and Quemada (2011); Li et al. (2015); Blanco-Canqui et al. (2015)
Zero tillage[a]	0-9	-5	-20	+5	-5	-20	+5	Cantero-Martínez et al (2003); Sun et al. (2011); Morell et al. (2011b); Soane at al. (2012); Mangalassery et al (2015); Troccoli et al (2015)
	10-25	+-0	-10	+10	+40	+20	+50	Sun et al. (2011); Soane et al. (2012); Troccoli et al. (2015)
Reduced tillage	0-9	-2	-10	+10	-	-	-	Cantero-Martínez et al (2003); Sun et al. (2011); Morell et al. (2011b); Troccoli et al. (2015); Townsend et al. (2016a)
	10-25	+-0	-10	+10	-	-	-	Sun et al. (2011); Troccoli et al. (2015); Townsend et al. (2016a)
Residue management		+-0	-10	+10	+-0	-10	+10	Pituello et al. (2015) Lehtinen et al. (2014)
Fertilisation with animal manure		-	-	-	+25	+10	+40	Meijide et al. (2007);
Optimised fertiliser application		-	-	-	+3	-30	+35	Brisson et al (2010)
Crop rotations (with legumes)		-	-	-	+30	+20	+50	Preissel et al. (2015)

Note [a] In Aragon expert opinion identified that the actual implementation of reduced till is very similar in terms of effects and costs is very similar to zero till, and therefore only zero-till was implemented in the model.

2.5.2.2 *Nutrient availability*

SOC management measures may allow substitution of organic and/or inorganic fertiliser application due to improved nutrient availability. For example, Carvalho et al. (2005) found that for an increase in SOC content from 1% to 2%, resulted in up to 62 kg N ha^{-1} becoming available to the crop. However, for some of the investigated SOC management measures such as zero and reduced tillage and residue management, no substitution of fertiliser through increased availability of nutrients is possible in the years following adoption due to immobilisation (Luxhøi et al. 2008); in fact, nutrient availability may temporarily decrease. Together with optimised fertiliser application in Aragon, fertiliser replacement potential is greatest for N fixing cover crops (legumes). However, these measures also have the greatest variation in N substitution possibilities. For the following years, replacement potential is greatest for N fixing cover crops (e.g., legumes). However, cover crops also have the greatest variation in N substitution possibilities.

Generally, effects on nutrient availability are likely to affect N, P and K availability. It would be interesting to consider impacts of SOC management measures on N, P and K separately. However, since reliable data from field experiments is lacking, this would require a series of assumptions that are not necessarily productive to generate more accurate or reliable model outcomes. Given the above, the assumed effects on nutrient availability as reported in Table 7 refer to crop specific N requirements and corresponding ratios of P and K requirements. Regarding SOC measures that are only considered for Aragon, Spain, mineral fertiliser can fully be replaced by organic fertiliser (for maize, some mineral fertiliser would need to be added to the organic application). Assumed reductions in fertiliser requirements of 23% from the baseline average optimised fertiliser applications are based on Van Alphen and Stoorvogel (2000).

An average price of € 0.8 kg^{-1} fertiliser is applied to derive at an estimate of the difference that fertiliser substitution would have on farm gross margins. The value of € 0.8 kg^{-1} fertiliser results from recommended fertiliser requirements divided by the variable fertiliser costs per ha listed in the SAC Farm Management Handbook 2013/14 (SAC 2013) for the 'mean' yield scenarios. Of course, there is a possibility that a certain level of replacement due to SOC management measures could result in less operations necessary, but thresholds for this are likely to vary across crop types and farm types and are difficult to establish and were therefore not considered.

Table 7. Fertiliser substitution effects (kg ha^{-1} fertiliser) for SOC measures

			Scotland			Aragon	
SOC measures	Year	Mean	Min	Max	Mean	Min	Max
Cover crops (legume)		30	50	10	30	50	10
Cover crops (non-legume)		+-0	15	-5	+-0	15	-5
Zero tillage	0-5	-10	5	-15	-5	5	-15
	6-25	+-0	40	-10	13	40	-10
Reduced tillage	0-5	+-0	5	-5	-	-	-
	6-25	+-0	20	-5	-	-	-
Residue management	0-5	-10	5	-15	-10	5	-15
	6-25	5	40	-10	15	40	-10
Fertilisation with animal manures		-	-	-	+-0	+-0	+-0
Optimised fertiliser application	0-5	-	-	-	+-0	+-0	+-0
	6-25	-	-	-	28	62	-6
Crop rotations (with legumes)	0-5	-	-	-	+-0	+-0	+-0
	6-25	-	-	-	62	74	25

Note: Negative values for fertiliser substitution effects reflect an increase in fertiliser needs, which in turn implies a decrease in farm gross margins entering the farm level model.

2.5.2.3 *Weed and pest control*

With respect to weed control and pesticide/fungicide use, changes were defined as percentage changes of the different SOC management measures from the mean expenditure on weed control as reported in the SAC Farm Management Handbook 2013/14 (SAC 2013). Changes in costs associated with weed and pest control, and implied absolute changes in costs, are assumed to be similar for Scotland and the Aragon case study (Table 8).

Table 8. Percentage (%) changes in weed control and spraying costs for SOC management measures

	Scotland			Aragon		
SOC measures	Mean	Min	Max	Mean	Min	Max
Cover crops (legume and non-legume)	+-0	-20	20	+-0	-20	20
Zero tillage	30	+-0	60	25	+-0	50
Reduced tillage	20	+-0	40	-	-	-
Residue management	10	+-0	20	10	+-0	20
Fertilisation with animal manures	-	-	-	+-0	+-0	+-0
Optimised fertiliser application	-	-	-	+-0	+-0	+-0
Crop rotations (with legumes)	-	-	-	+-0	+-0	+-0

Note: Scotland: Changes relative to baseline as reported in SAC (2013): winter wheat €160 ha^{-1}; winter barley €110 ha^{-1}; spring barley €62.5 ha^{-1}; winter oats €75 ha^{-1}; spring oats €65 ha^{-1}; Spain: Note: Changes relative to baseline: wheat (rainfed) €14 ha^{-1}; wheat (irrigated) €26 ha^{-1}; barely (rainfed) €20 ha^{-1}; barley (irrigated) €32 ha^{-1}; maize (irrigated) €78 ha^{-1}; alfalfa (irrigated) €36 ha^{-1}; almond (rainfed) €50 ha^{-1}; vineyard (rainfed) €138 ha^{-1}; olives (rainfed) €19 ha^{-1}

2.5.2.4 *Cost of field operations*

SOC management measures can result in changes in costs for field operations (see e.g. Morris et al. 2010), that is, use of machinery and associated time and fuel costs for ploughing, tillage, seeding and, in case of residue management, bailing of straw. The values used in the farm level models are reported in Table 9, developed using expert judgment and for the Scottish case study region baseline figures for field operations from SAC (2013). Cover crops are assumed to be associated with a slight increase related to the need for seeding and killing of the cover crop (e.g., Pratt et al. 2014). Zero and reduced tillage are assumed to result in no costs for ploughing and a slight decrease is assumed for tillage operations (Morris et al. 2010) and residue management (no need for bailing of straw). In the case of optimised fertiliser application, the cost refers to the cost of performing soil analysis.

Table 9. Changes in field operation costs (€ ha^{-1}) for SOC management measures (Scotland)

	Scotland			Aragon		
SOC measures	Mean	Min	Max	Mean	Min	Max
Cover crops (legume and non-legume)	26.3	8.8	43.8	30	10	50
Zero tillage	-87.5	-105	-70	-10	0	-20
Reduced tillage	-70	-87.5	-52.5	-	-	-
Residue management	-17.5	-35	-8.8	-20	-40	-10
Fertilisation with animal manures	-	-	-	140	75	200
Optimised fertiliser application	-	-	-	6	3	10
Crop rotations (with legumes)	-	-	-	0	0	0

2.5.2.5 *Seed costs (cover crops)*

Seed costs for establishing a cover crop vary widely depending on the type of cover crop used. The choice of cover crop (legume or non-legume) can affect the nutrient availability effect. We assumed seed costs to be €70 ha^{-1} (Scotland, Aragon) on average if they entail legumes, and €30 ha^{-1} (Scotland) and €40 ha^{-1} (Aragon) on average if they do not. Seed costs may be as low as €17.5 ha^{-1} for some rye grass varieties but may exceed €100 ha^{-1} for some legumes. Consequently, seed costs for both Scotland and Aragon vary between a minimum of €20 ha^{-1} and a maximum of € 120 ha^{-1}.

2.5.2.6 *Forgone value of straw (residue management)*

As a final cost element specifically related to residue management is the forgone production value of straw. How straw is used after it is being bailed and hauled depends on local demand for straw within the same farm or as a commodity sold to other users (e.g. livestock farms or biomass plants). We assume that changes in straw production are proportional to yield change. Table 10 reports baseline straw yields, which are multiplied by the expected yield change (equal to one if there is no change in yield) and the value of straw in € t^{-1} to derive the annual value of the forgone production of straw used in the farm models. Values of straw are assumed to be €35 t^{-1} on average for both Scotland and Aragon, and vary from €13.1 t^{-1} to €56.9 t^{-1} for Scotland, and from €25 t^{-1} to €45 t^{-1} for Aragon.

Table 10. Baseline straw yields (t ha^{-1})

Crops	Scotland	Aragon
Winter wheat	4.2	-
Spring barley	2.9	-
Spring oats	3	-
Wheat (rainfed)	-	4.9
Wheat (irrigated)	-	6.6
Barley (rainfed)	-	5.8
Barley (irrigated)	-	6.2

Source Scotland: SAC Farm Management Handbook 2013/14 (SAC 2013); Source Spain: Moragues et al. 2006; Urbano 2002; Francia et al. 2006; Pordesimo et al. 2004

3 Results

3.1 Scotland

Figure 3 shows the changes in farm gross margins for the three farm types investigated for Scotland and the SOC management measures compared to the baseline. All crop farm types benefit financially from both reduced and zero tillage measures in the long term (see Figure 3). Crop yields decrease by 5% (reduced tillage) and 2% (zero tillage) for the first 5 years, and increase by 5% in subsequent years. The main benefit arises from savings in input costs associated with tillage. Residue management results in the largest negative effect on farm gross margins (up to –6%) in all three farm types. Crop yields remain unchanged under this measure, but a substantial loss in straw revenues reduces farm gross margins. The cover crop measures have a small but negative effect (< -3%) across all farm types.

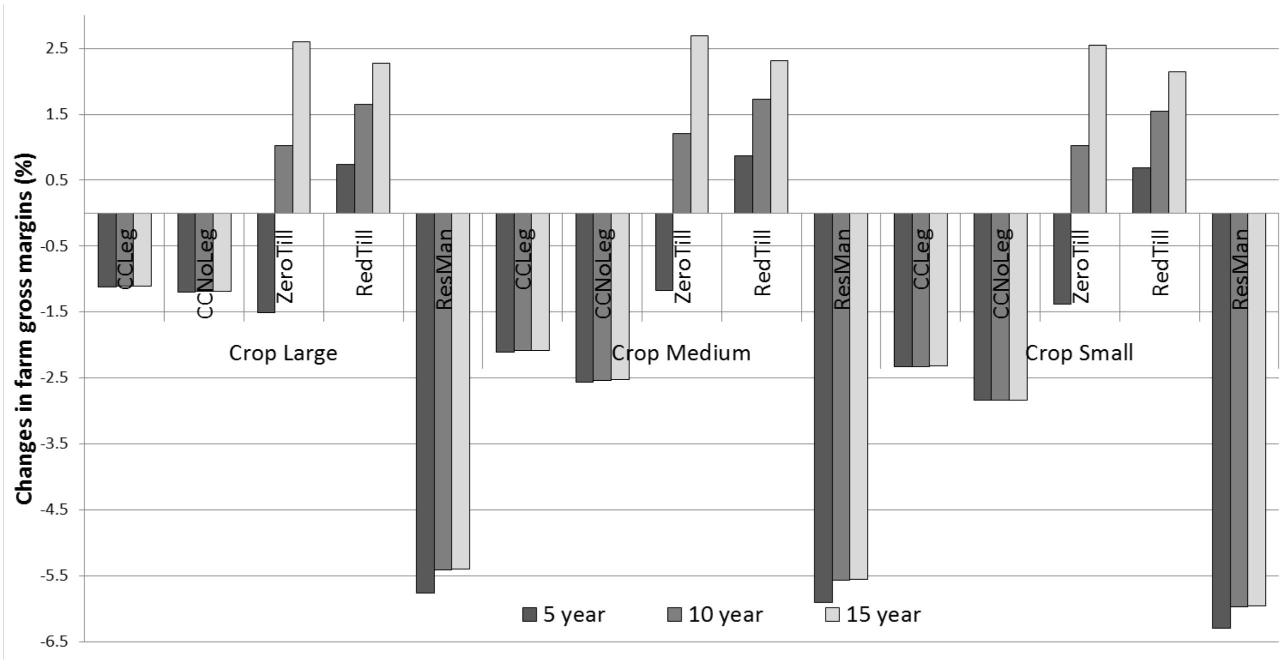

Figure 3. Percentage change in gross margins under different SOC options compared to the baseline for Scottish farm groups: CCleg = cover crop with legume; CCNoLeg = cover crop without legumes; ZeroTill = zero tillage; RedTill = reduced tillage; ResMan = residue management

Results of the sensitivity analysis (which is run for the four cases: $Y_{max}C_{max}$, $Y_{max}C_{min}$, $Y_{min}C_{max}$ and $Y_{min}C_{min}$) for the Scottish context are presented in Figure 4 (see also supplementary material Table S1). Assumptions on crop yields have a greater effect on farm gross margins than variation in input costs. An exception is residue management, where farm gross margins are equally sensitive to assumptions regarding yield effects and changes in input costs, which are in particular associated with the forgone value of straw. Residue management only achieves a positive effect for upper bound yield effects and lower bound assumptions on input costs ($Y_{max}C_{min}$). Additionally, farm gross margins for residue management can decrease considerably by up to 30%.

There are only small differences between the two cover crop measures (legume and non-legume) across all four cases. Legume cover crops have greater positive yield effects, especially at the upper bound (Y_{max}). However, seed costs can be considerably higher for cover crops using legumes. This is reflected in lower farm gross margins compared to non-legume cover crops in the $Y_{min}C_{max}$ case. The cover crop SOC management measures are overall quite robust to changes in assumptions; i.e., effects on farm gross margins are in the range of -5% to +5% across the four sensitivity analysis cases. However, cover crop measures lack the potential for substantial positive effects that are particularly apparent for zero and reduced tillage measures in the $Y_{max}C_{min}$ case (up to 14% increase after 5 years).

Reduced tillage performs always better or at least equally well as zero tillage across all time periods, and yield effects are key to both tillage measures to arrive at positive effects on farm gross margins. Additionally, zero tillage appears to be particularly sensitive to yield effects in earlier years. Figure 4 also shows that the patterns of sensitivity found do not differ much across farm types.

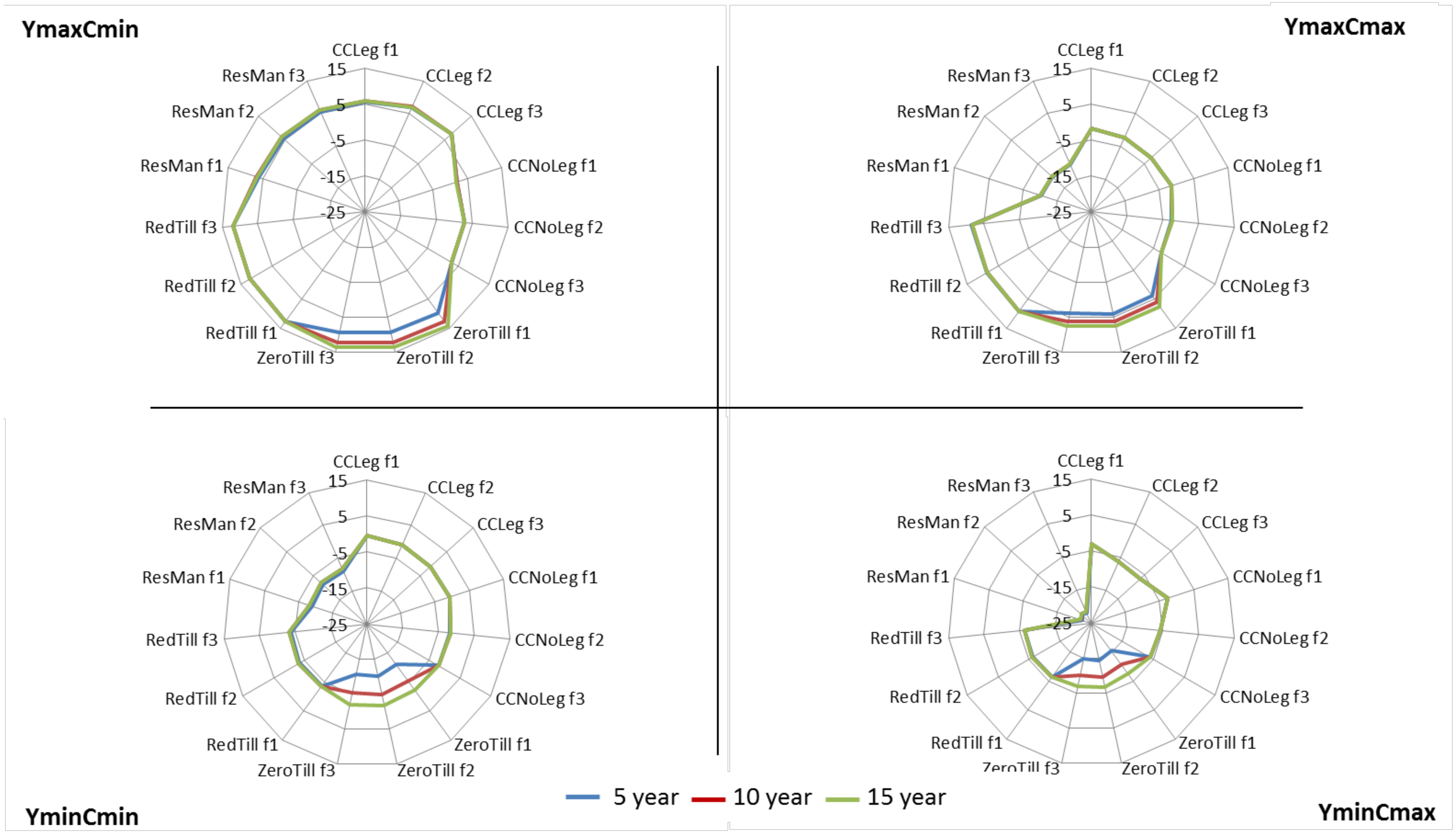

Figure 4. Percentage changes in farm gross margins compared to the baseline under sensitivity analysis of crop yield and crop gross margins: CCleg = cover crop with legume; CCNoLeg = cover crop out legumes; ZeroTill = zero tillage; RedTill = reduced tillage; ResMan = residue management; f1 = large sized crop farm group; f2 = medium sized crop farm group and f3 = small sized crop farm group

3.2 Aragon

Unlike Scottish farms in the study, relative farm gross margin effects of Aragon farms lack variability between the three farm types for the SOC management scenarios. The main reasons are the interaction of crop and livestock systems on Scottish farms, and the availability of additional farm-type specific input parameters, for example regarding family labour, for Scottish farms. Because differences in relative farm gross margin effects between farm types are negligible for Aragon, the results displayed in Figure 5 and in the following sensitivity analysis (Figure 6) show average relative gross margin effects across all farm types.

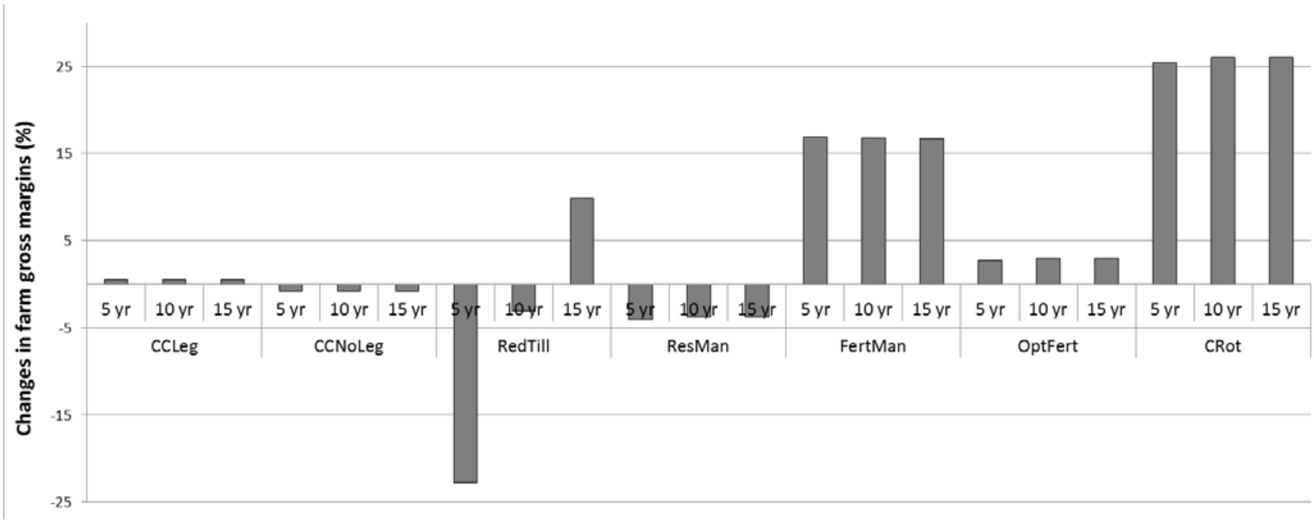

Figure 5. Percentage changes in farm gross margins under different SOC options compared to the baseline for on farm in Aragon region of Spain: CCleg = cover crop with legume; CCNoLeg = cover crop with no legume; ZeroTill = zero tillage; RedTill = reduced tillage; ResMan = residue management; FertMan = fertilisation with animal manure; OptFert = optimal use of fertiliser and CRot = crop rotation

All of the SOC measures projected to increase yields of the main crops except for tillage management in earlier time periods and residue management. Tillage management is assumed to result in a slight decrease in yield (5%) in the first 10 years, but yield increases substantially (40% relative to business as usual) after that. This is reflected in a 22% and 5% reduction in farm gross margins after 5 and 10 years, but an increase in farm gross margins of 10% after 15 years (Figure 5). There is no change in yields expected for the residue management measure in the baseline scenario, but due to forgone revenue from straw, farm gross margins decrease by up to 4%. There is no substantial change in farm gross margins under both of the cover crop options. The increase in crop yields and increases in input costs almost off-set each other for these management measures. Fertiliser management and crop rotation result in increased farm gross margins, which can be largely explained by crop yields being assumed to increase by up to 30%.

Similar to the Scottish case study, the sensitivity analysis for the Aragon case study shows that effects on farm gross margins are more sensitive to changes in crop yields than to changes in input costs (Figure 6; see also supplementary material Table S2). SOC management measures have a positive effect for the case of upper bound crop yields ($Y_{max}C_{max}$ and $Y_{max}C_{min}$) except for cover crops (non-legume) and residue management, which does not show a positive effect in all four sensitivity analysis cases. Tillage management measures initially (by 5 years) show a negative effect, which is reversed in later years. The greatest positive effect on farm gross margins is found for crop rotation management measures when yields are at the maximum and input costs are at the minimum ($Y_{max}C_{min}$). Fertilisation with animal manure and crop rotation (with legumes) are relatively robust in their positive effect across all four combinations of upper and lower bound estimates for crop yield effects and input costs. This differs from the pattern found for optimised fertiliser application. In the cases of upper bound crop yields (Y_{max}), it is only second to the crop rotations measure in its positive effect on farm gross margins. However, optimised fertiliser application shows the largest negative effect on farm gross margins by 15 years (minus 25%) if yield effects are assumed to be at the lower bound (Y_{min}).

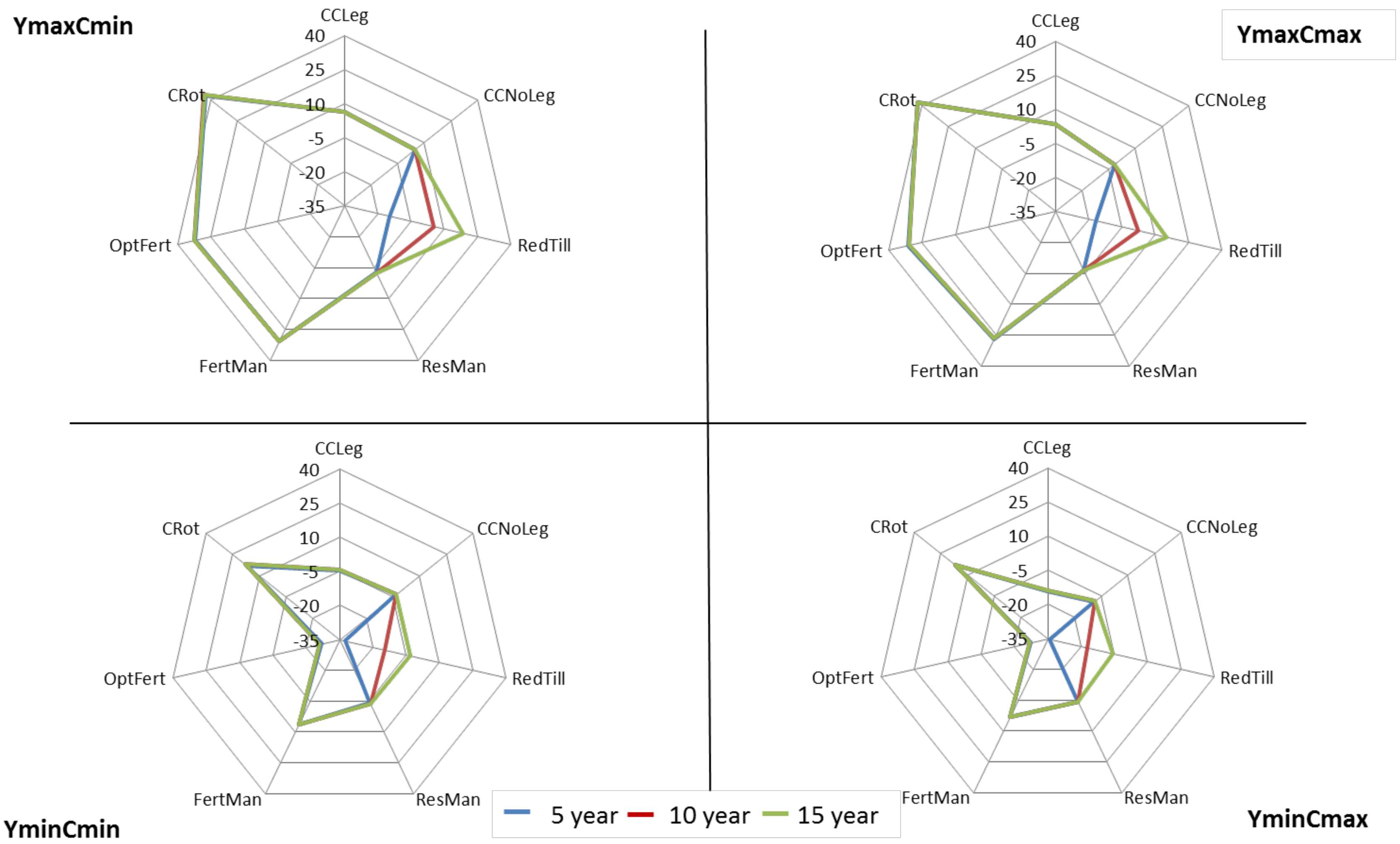

Figure 6. Percentage changes in farm gross margin compared to the baseline under sensitivity analysis of crop yield and crop gross margins on farms in Aragon region of Spain margins CCleg = cover crop with legumes; CCNoLeg = cover crop without legumes; ZeroTill = zero tillage; RedTill = reduced tillage; ResMan = residue management; FertMan = fertilisation with animal manure; OptFert = optimal use of fertiliser and CRot = crop rotation

Although, as stated earlier, the difference in gross margin effects is negligible across all three farm types for Aragon, farm gross margin effects differ in absolute terms (Figure 7). The extent of the effect very much represents the size of the farm: the larger the size of the farm, the greater the absolute change in farm gross margins.

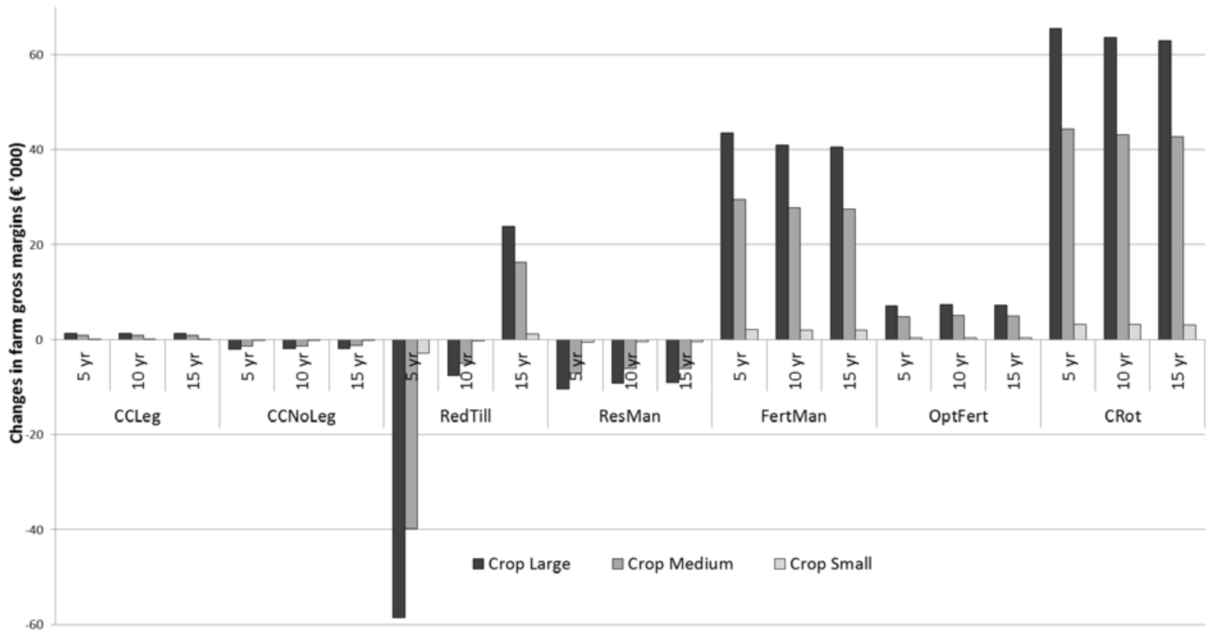

Figure 7. Absolute changes in farm gross margins (GM) compared to the baseline GM for farm groups in Aragon region of Spain: CCleg = cover crop with legume; CCNoLeg = cover crop without legumes; ZeroTill = zero tillage; RedTill = reduced tillage; ResMan = residue management; FertMan = fertilisation with animal manure; OptFert = optimal use of fertiliser and CRot = crop rotation

4. Discussion

Tillage management was found to have a positive effect on farm gross margins in both case study regions in later years. As pointed out by Townsend et al. (2016b) in a study investigating farm level impacts of tillage management in England using a bio-economic optimisation model, actual financial benefits (i.e. farm net margins) of reducing tillage intensity can be higher than gross margin effects suggest if benefits of, for example, in terms of reduced labour costs or machinery use are taken into account. Townsend et al.

(2016b) find that the magnitude of yield decrease that would be required to off-set any benefits of tillage management measures in terms of gross margins tends to increase with decreasing tillage intensity; however, the benefits of tillage are affected by crop and rotation (Townsend et al. 2016a) and the importance of soil water retention (Troccoli et al. 2015). For the baseline scenario, we also find that zero tillage ultimately results in greater gross margin gains compared to reduced tillage. However, the comparative advantage disappears if input costs savings are limited, for example because of an increased need for weed and pest control.

Additionally, in both Scotland and Aragon, zero tillage shows positive effects only in later years (due to a delay in yield effects), whereas initially farm gross margins decrease. This can have important consequences for uptake, because the lagged effect can contribute to perceived uncertainty regarding impacts on farm productivity, which Prager and Posthumus (2010) regard as a barrier to uptake. Consequently, risk averse farmers aiming to adopt SOC measures would likely opt for alternative management measures or retain their current management.

Therefore, if zero tillage was to be promoted as a SOC management measure, the factors determining yield in early years of implementation need to be better understood to increase the probability of less adverse yield effects in the first years, thus reducing uncertainty.

The results show that there is limited variability in effects of SOC measures between different farm types. All of the crop farms are assumed to be on similar soil type and have very similar management measures. The only major difference between the farms is size of farm and scale of production. Our assumption behind the changes in crop yields and costs of production is generalised across all farm types. A more detailed set of assumptions for each farm type would most probably bring out some variability in the effects of the SOC management measures on different farm types. This could include differentiating the effect of the soil management on SOC and yields by farm type and soil type. This may be achieved by using a dynamic and deterministic model of the soil carbon and nitrogen dynamics (e.g. Taghizadeh-Toosi & Olesen, 2016; Holzworth et al., 2014; Parton and Rasmussen, 1994).

The results of the sensitivity analysis demonstrate the relative robustness of SOC management measures from a financial perspective at the farm level. The information derived from this study should not be used as a predictive tool for policy makers and farmers; rather, we seek to demonstrate important considerations that affect the uptake and profitability of SOC management measures. While these considerations need to be carefully evaluated by decision makers on a case-to-case basis, the results presented in this paper help to identify SOC measures that are most robust to changes in underlying assumptions regarding yield and nutrient availability effects.

Gross margin effects of SOC management measures on farm gross margins are found to be more sensitive to a change in crop yields than to changes in input costs. Therefore, it may be concluded that effects of SOC management measures on fertiliser requirements (and associated changes in cost) are not making a large difference to farm gross margins. However, this could change if the prices of fertiliser/other inputs change relative to crop prices compared to the baseline. It may also be important to take a careful look at fertilisation effects through experiments and modelling studies (e.g. for cover crops, Li et al., 2015; Autret et al., 2016; and inorganic fertiliser, Riley 2016; Godde et al 2016), thereby better understanding the biophysical relationships that underpin them.

The results of modelling suggest utilising manure and crop rotations would be financial beneficial to the farmers; however, fertilisation with manure is less widely adopted in Aragon than crop rotations (Sánchez et al. 2016b). One likely reason for the difference in uptake is that crop rotations (with legumes) is the only SOC management measure investigated that currently receives direct subsidies under the Common Agricultural Policy (CAP) in Aragon. Also, the modelling framework assumes that the farmers are profit maximisers, however for a variety of reasons (Moran et al., 2013; Buri et al, 2016), farmers may not behave rationally. Especially in relation to soil management, farmers' behaviour may also be motivated by other factors such as perceived workability of the soil, soil health for future generations or short-term financial benefits. The salience of such motivations for improved soil management is, however, unclear and remains an area that needs further investigation. In addition, the model assumes all farms within a farm type are the same; whereas in reality they will differ in their structure and their financial and biophysical characteristics (Moran et al., 2013).

The robustness of effects on farm gross margins differs across SOC management measures in the case study regions. This finding points to a need for a more detailed understanding of local environmental and farm management factors that affect yields and input costs. In the absence of such information being available to farmers, measures such as cover crops in Scotland and Aragon, for example, may be attractive to risk averse farmers even without additional financial incentives that could serve as an insurance against reduced productivity (Deeks et al. 2008). Despite lower projected positive effects on gross margins compared to alternative SOC management measures, the effects of the cover crop measure on farm gross margins is relatively robust to variation in effects on yield and input costs. Given that cover crops can have a considerable impact on increasing SOC stocks, ways to encourage further uptake should be developed. Fertilisation with animal manures and crop rotation (with legumes) are found to have robust effects on gross margins in the Aragon case study. Both measures are reported to have considerable potential to increase SOC stocks, and positive effects on farm gross margins are found to be relatively robust across all four combinations of upper and lower bound estimates for crop yield effects and input costs. This is in contrast with optimised fertiliser application, which can yield considerable positive estimates, but which is also found to decrease gross margins if yield effects are at their lower bound, therefore making it relatively unattractive to risk averse farmers.

Using plausible ranges of key parameters regarding the effects on nutrient availability, yield effects, pest control and farming operations derived from expert knowledge and guided by available literature may be considered second-best to a complex bio-economic model. However, rather than aiming for a detailed understanding of bio-physical processes underpinning crop production or environmental impacts (e.g., Reckling et al. 2016), this paper investigates the potential *range of variation* in gross margins associated with changes in SOC management for representative farms in a study region. In this respect, using plausible ranges rather than modelled estimates for changes in inputs and yield is advantageous since it allows greater control over key determinants of farm gross margins; and circumvents problems arising from uncertainty associated with defining bio-physical parameters at the farm scale for a 'representative farm' in a particular study region.

Although based on farming system analysis, the farm level model, ScotFarm only includes changes in yield and input costs of production under all SOC measures. The model then adjusts the farming activities based on those changes. SOC management measures may not only affect yields and input costs, for example through fertilisation effects, but also other aspects that affect farm level economics that were not covered in this study. This includes effects on timing and seasonal of labour resource availability and capital costs associated with switching to a different management. Anecdotal evidence also points to impacts of SOC management measures on, for example, soil structure and workability.

The results do not consider interaction effects between SOC measures, which could affect their effect on yield and input costs considered in the model. For example, cover crops may be combined with a changed tillage system and crop rotation (Gillier et al. 2015). Additionally, because we consider only variable cost, potential synergies related to, for example, machinery use across various SOC management measures are not considered.

It is assumed that a farmer can easily implement the management measures and does not face barriers regarding access to capital and technology (machinery) required for their implementation. This assumption was necessary due to the widely unknown reference conditions in Scottish arable farms. McVittie et al. (2014) report findings from a series of workshops with farm consultants on barriers for uptake of the four management measures included in this study. Access to capital or machinery was not identified as a barrier. Sánchez et al. (2016b) identify barriers for uptake of agricultural practices, including measures that enhance SOC, based on an econometric analysis of farm surveys in Aragon, Spain. Financial incentives and access to technical advice were amongst the main factors defining farmers' barriers to implementation.

Our results demonstrate the sensitivity of financial gains of SOC management on the farm level to assumptions regarding yield effects and input costs. To some degree, these can be influenced at the farm level, for example through careful weed and pest management following the switch to zero or reduced tillage. Nevertheless, from the farmers' perspective, the actual financial impacts of implementing the SOC management measures is unknown and at least partially dependent on external factors such as weather conditions and market prices. This makes investment into changes in management measures a risky choice. An extension of the model should therefore incorporate an element of risk, for example through the development of probabilistic outcomes for yield effects and costs over the years. This aspect is of interest, because SOC management measures may contribute to yield reliability (that is, to reducing variability in yield) over time, for example by improving the water holding capacity of the soil (Zibilske and Bradford 2007; Powlson et al. 2014) and therefore the capacity to overcome longer periods of drought. This may become increasingly important in the context of climate change adaptation (Williams et al. 2016).

In order to evaluate the SOC management measures from a broader policy perspective, it is important to consider how they perform in terms of changes SOC stocks, especially in areas with low SOC stocks and a high risk of further decline in SOC under the current management regime. Further research should consider linking farm level models with a more detailed SOC model to allow assessments of cost-effectiveness of management measures, and the development of regional models that optimise the allocation of management measures according to economic and soil management (SOC stocks) objectives.

Further, impacts of SOC management measures on greenhouse gas emissions and other co-effects including improvements in water quality for example related to nitrogen leaching (Reckling et al. 2016), or biodiversity, should be assessed (Glenk and Colombo 2011). These benefits to the public can play an important role in justifying government support for improved SOC management, for example in the form of financial incentives for farmers that have previously been found to be a major factor in decisions to adopt SOC management measures.

5. Conclusions

Knowledge on private financial benefits associated with SOC management measures such as reduced tillage or cover crops is limited but important for guiding policy support to encourage their uptake. This study finds that there are considerable differences in farm gross margins across a range of suitable SOC management measures and across a number of representative arable farms in two EU-regions (Scotland, UK; Aragon, Spain). Two measures have been identified for each of the regions that combine the possibility of positive farm gross margin effects with relatively low sensitivity to changes in yield effects and effects on input costs.

For Scotland, the most promising measures in terms of gross margin effects are reduced tillage intensity and cover crops. Because reduced tillage intensity shows negative gross margin effects in early years of adoption and cover crops have either small positive or negative effects depending on the magnitude of yield effects and changes in input costs, it is questionable that these measures would be adopted in the absence of financial incentives. The possibility of payments to farmers through for example the Scottish Rural Development Programme should be explored. Because both measures reduce surface run-off, payments could be targeted to areas with greater erosion risk and where arable farming is found to contribute significantly to diffuse water pollution.

Fertilisation with animal manures and crop rotations with legumes are the two measures with a promising outlook in terms of gross margin effects for Aragon. Crop rotations (with legumes) is more widely adopted compared to fertilisation with animal manures. While this is unlikely to be entirely attributable to financial incentives, the fact that subsidies are currently available for crop rotations (with legumes) certainly plays a role. Because of the considerable positive effect on gross margins, the advantages and disadvantages of ceasing financial incentives for crop rotations (with legumes) to support other measures such as fertilisation with animal manures should be explored.

Acknowledgements

The work was funded by SmartSOIL (Grant Agreement No. 289694), co-funded by the European Commission, Directorate General for Research & Innovation, within the 7th Framework Programme of RTD, Theme 2 – Biotechnologies, Agriculture & Food. The work of Klaus Glenk, Shailesh Shrestha and Cairistiona F.E. Topp have been co-financed by the Scottish Government through the Rural Affairs and the Environment Portfolio Strategic Research Programme 2016–2021, Theme 2 (Theme 2: Productive and Sustainable Land Management and Rural Economies).

References

Ahmad, Z., 1997. Modelling the impact of agricultural policy at the farm level in the Punjab, Pakistan. Phd thesis. University of Nottingham

AFBINI, 2012. FAPRI-UK 2012 baseline projections 2012 – 2021. https://www.afbini.gov.uk/publications/fapri-uk-2012-baseline-projections-december-2012-excel-figures

Álvaro-Fuentes, J., Easter, M., Cantero-Martínez, C., Paustian, K., 2011. Modelling soil organic carbon stocks and their changes in the northeast of Spain. European Journal of Soil Science, 62, 685–695

Álvaro-Fuentes, J., Morell, F.J., Plaza-Bonilla, D., Arrúe, J.L., Cantero-Martínez, C., 2012. Modelling tillage and nitrogen fertilization effects on soil organic carbon dynamics. Soil & Tillage Research 120, 32–39

Autret B., Mary B., Chenu C., Balabane M., Girardin C., Bertrand M., Grandeau G., Beaudoin N. 2016. Alternative arable cropping systems: A key to increase soil organic carbon storage? Results from a 16 year field experiment. Agriculture, Ecosystems & Environment 232, 150–164

Arrouays, D., Balesdent, J., Germon, J.C., Jayet, P.A., Soussana, J.F., Stengel, P. (Eds.), 2002. Stocker du Carbone dans les Sols Agricoles de France? Contribution a` la Lutte Contre l'Effet de Serre. Expertise Collective INRA, Paris, France, (in French), pp 332

Ball, B.C., Franklin, M.F., Holmes, J.C., Soane, B.D., 1994. Lessons from a 26-year tillage experiment on cereals. In: Proc. 13th International Conference of the International Soil Tillage Research Organisation, Aalborg, Denmark, Vol. 2, pp. 757–762

Bhogal, A., Chambers, B.J., Whitmore, A.P., Powlson, D.S., 2007. The Effect of Reduced Tillage Practices and Organic Matter Additions on the Carbon Content of Arable Soils. Scientific Report SP0561. Department of Environment, Food and Rural Affairs, London, UK, 47pp

Binfield, J., Patton, M. and Feng, S., 2015. EU and UK FAPRI Baseline 2015 – Briefing Book. Agri-Food and Biosciences Institut. Belfast, UK., 49pp.

Blanco-Canqui, H., Shaver, T.M., Lindquist, J.L., Shapiro, C.A., Elmore, R.W., Francis, C.A., Hergert G.W. 2015. Cover Crops and Ecosystem Services: Insights from Studies in Temperate Soils. Agronomy Journal 107, 2449–2474

Brisson, N., Gate, P., Gouache, D., Charmet, G., Oury, F.-X., Huard, F. 2010. Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. Field Crops Research 119, 201–212

Burbi, S., Baines, R. N., Conway, J.S. 2016. Achieving successful farmer engagement on greenhouse gas emission mitigation. International Journal of Agricultural Sustainability, 14, 466-483

Carvalho, M., Basch, G., Alpendre, P., Branda˜o, M., Santos, F., Figo, M., 2005. A adubacao azotada do trigo de sequeiro: o problema da sua eficiencia. Melhoramento 40, 5–37 (in Portuguese)

Cantero-Martínez, C., Angas, P., Lampurlanés, J. 2003. Growth, yield and water productivity of barley (Hordeum vulgare L.) affected by tillage and N fertilization in Mediterranean semiarid, rainfed conditions of Spain. Field Crops Research 84, 341–357

Cordell, D., Drangert, J.-O., White, S., 2009. The story of phosphorus: Global food security and food for thought. Global Environmental Change 19(2), 292–305

Deeks, L., Posthumus, H., Rickson, J., Fenn, I., Bowyer, C., Baldock, D., Heyn, N., 2008. Sustainable agriculture and soil conservation. Case study report – United Kingdom. Joint Research Centre. European Commission.

Díaz-Ambrona, C.H., Mínguez, M.I., 2001. Cereal–legume rotations in a Mediterranean environment: biomass and yield production. Field Crops Research 70(2), 139–151

Dominati, E., Patterson, M., Mackay, A., 2010. A framework for classifying and quantifying the natural capital and ecosystem services of soils. Ecological Economics 69, 1858–1868

EC, 2011. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Roadmap to a Resource Efficient Europe (COM (2011) 571 final). Official Journal of the European Union, Brussels

Feng, H., Kling, C.L., 2005. The Consequences of Co-benefits for the Efficient Design of Carbon Sequestration Programs. Canadian Journal of Agricultural Economics 53(4), 461–476

Follet, R.F., 2001. Soil management concepts and carbon sequestration in croplands soils. Soil & Tillage Research 61(1), 77–92

Francia, E., Pecchioni, N., Nicosia, O.L.D., Paoletta, G., Taibi, L., Franco, V., Odoardi, M., Stanca, A.M., Delogu, G., 2006. Dual-purpose barley and oat in a Mediterranean environment. Field Crops Research 99, 158–166.

Freibauer, A., Rounsevell, M.D.A., Smith, P., Verhagen, A., 2004. Carbon sequestration in European agricultural soils. Geoderma 122, 1–23

Fresco, L.O., 1988. Farming Systems Analysis – an introduction. Tropical Crops Communication No. 13. Dept. of Tropical Crop Science, University of Wageningen, The Netherlands

Gabriel, J.L., Quemada, M., 2011. Replacing bare fallow with cover crops in a maize cropping system: Yield, N uptake and fertiliser fate. European Journal of Agronomy 34(3), 133–143

Giller, K., Andersson, J., Corbeels, M., Kirkegaard, J., Mortensen, D., Erenstein, O., Vanlauwe, B. 2015 Beyond conservation agriculture. Front Plant Sci 6. doi:10.3389/fpls.2015.00870

Glenk, K., Colombo, S., 2011. Designing policies to mitigate the agricultural contribution to climate change: an assessment of soil based carbon sequestration and its ancillary effects. Climatic Change 105, 43–66

Glenk, K., McVittie, A., Moran, D., Smith, P., Yeluripati, J.B., Ghaley, B.B., Porter, J.R., 2013. Deliverable D3.1: Soil and Soil Organic Carbon within an Ecosystem Service Approach Linking Biophysical and Economic Data. Report for EU FP7 SmartSOIL (Grant Agreement N° 289694). Available at http://smartsoil.eu/

Godde C., Thorburn P., Biggs J., Meier E. 2016. Understanding the Impacts of Soil, Climate, and Farming Practices on Soil Organic Carbon Sequestration: A Simulation Study in Australia. Frontiers in Plant Science 7. doi:10.3389/fpls.2016.00661

Guardia, G., Tellez-Rio, A., García-Marco, S., Martin-Lammerding, D., Tenoriom J., Ibáñezm, M., Vallejo, A., 2016. Effect of tillage and crop (cereal versus legume) on greenhouse gas emissions and Global Warming Potential in a non-irrigated Mediterranean field. Agriculture, Ecosystems & Environment 221, 187–197. doi:10.1016/j.agee.2016.01.047

Holzworth, D.P., Huth, N.I., deVoil, P.G., Zurcher, E.J., Herrmann, N.I., McLean, G., Chenu, K., van Oosterom, E.J., Snow, V.O., Murphy, C., Moore, A.D., Brown, H., Whish, J.P.M., Verrall, S., Fainges, J., Bell, L.W., Peake, A.S., Poulton, P.L., Hochman, Z., Thorburn, P.J., Gaydon, D.S., Dalgliesh, N.P., Rodriguez, D., Cox, H., Chapman, S., Doherty, A., Teixeira, E., Sharp, J., Cichota, R., Vogeler, I., Li, F.Y., Wang, E., Hammer, G.L., Robertson, M.J., Dimes, J.P., Whitbread, A.M., Hunt, J., van Reesm H., McClelland, T., Carberry, P.S., Hargreaves, J.N.G., MacLeod, N., McDonald, C., Harsdorf, J., Wedgwood, S, Keating, B.A. 2014. APSIM - Evolution towards a new generation of agricultural systems simulation. Environmental Modelling & Software 62, 327-350

INE, 2009. Instituto Nacional de Estadística. National Statistics Institute. Spanish Statistical Office.

Justes, E., Mary, B., Nicolardot, B., 2009. Quantifying and modelling C and N mineralization kinetics of catch crop residues in soil: parameterization of the residue decomposition module of STICS model for mature and non mature residues. Plant and Soil 325, 171–185. doi:10.1007/s11104-009-9966-4.

Kahiluoto, H., Smith, P., Moran, D., Olesen, J.E., 2014. Enabling food security by verifying agricultural carbon. Nature Climate Change 4, 309–311

Khan, S.A., Mulvaney, R.L., Ellsworth, T.R., Boast, C.W., 2007. The myth of nitrogen fertilization for soil carbon sequestration. Journal of Environmental Quality 36, 1821–1832

Lal, R., 2004. Carbon sequestration in dryland ecosystems. Environmental Management 33(4), 528–544

Lal, R., Bruce, J.P., 1999. The potential of world cropland soils to sequester C and mitigate the greenhouse effect. Environmental Science & Policy 2, 177–185

Li X., Petersen S., Sørensen P., Olesen J. 2015 Effects of contrasting catch crops on nitrogen availability and nitrous oxide emissions in an organic cropping system. Agriculture, Ecosystems & Environment 199, 382–393.

Keating, B.A., McCown, R.L., 2001. Advances in farming systems analysis and intervention. Agricultural Systems 70, 555–579.

Lehtinen, T., Schlatter, N., Baumgarten, A., Bechini, L., Krüger, J., Grignani, C., Zavattaro, L., Costamagna, C., Spiegel, H. 2014. Effect of crop residue incorporation on soil organic carbon and greenhouse gas emissions in European agricultural soils. Soil Use and Management 30, 524–538

López-Bellido, R.J., Fontán, J.M., López-Bellido, F.J., López-Bellido, L., 2010. Carbon sequestration by tillage, rotation, and nitrogen fertilization in a Mediterranean Vertisol. Agronomy Journal 102, 310–318

Luxhøi, J., Elsgaard, L., Thomsen, I.K., Jensen, L.S., 2007. Effects of long-term annual inputs of straw and organic manure on plant N uptake and soil N fluxes. Soil Use and Management 23, 368–373

Luxhøi, J., Fillery, I.R.P., Murphy, D.V., Bruun, S., Jensen, L.S., Recous, S., 2008. Distribution and controls on gross N mineralization-immobilization-turnover in soil subjected to zero tillage. European Journal of Soil Science 59, 190–197

Mangalassery, S., Mooney, S.J., Sparkes, D.L., Fraser, W.T., Sjögersten, S., 2015. Impacts of zero tillage on soil enzyme activities, microbial characteristics and organic matter functional chemistry in temperate soils. European Journal of Soil Biology 68, 9–17. doi:10.1016/j.ejsobi.2015.03.001

McVittie, A., Ghaley, B.B., Molnar, A., Dibari, C., Karaczun, Z., Sánchez B., 2014. Deliverable D3.2: Report on the cost-effectiveness of SOC measures. Report for EU FP7 SmartSOIL (Grant Agreement N° 289694). Available at http://smartsoil.eu/

Meijide, A., Díez, J.A., Sánchez-Martín, L., López-Fernández, S., Vallejo A., 2007. Nitrogen oxide emissions from an irrigated maize crop amended with treated pig slurries and composts in a Mediterranean climate. Agriculture, Ecosystems & Environment 121, 383–394

Melero, S., López-Garrido, R., Madejón, E., Murillo, J., Vanderlinden, K., Ordóñez, R., Moreno, F., 2009. Long-term effects of conservation tillage on organic fractions in two soils in southwest of Spain. Agriculture, Ecosystems & Environment 133, 68–74. doi:10.1016/j.agee.2009.05.004.

Melero, S., Panettieri, M., Madejón, E., Macpherson, H., Moreno, F., Murillo, J.M., 2011. Implementation of chiselling and mouldboard ploughing in soil after 8 years of no-till management in SW, Spain: Effect on soil quality. Soil & Tillage Research 112, 107–113. doi:10.1016/j.still.2010.12.001

Moran D., Lucas A., Barnes A 2013. Mitigation win-win. Nature Climate Change 3, 611–613.

Moragues, M., García del Moral, L.F., Moralejo, M., Royo, C., 2006. Yield formation strategies of durum wheat landraces with distinct pattern of dispersal within the Mediterranean basin. Field Crops Research 95, 182–193

Morell, F.J., Lampurlanés, J., Álvaro-Fuentes, J., Cantero-Martínez, C., 2011a. Yield and water use efficiency of barley in a semiarid Mediterranean agroecosystem: Long-term effects of tillage and N fertilization. Soil & Tillage Research 117, 76–84

Morell, F.J., Cantero-Martínez, C., Lampurlanés, J., Plaza-Bonilla, D., Álvaro-Fuentes, J., 2011b. Soil carbon dioxide flux and organic carbon content: effects of tillage and nitrogen fertilization. Soil Science Society of America Journal 75, 1874–1884

Morris, N.L., Miller, P.C.H., Orson, J.H., Froud-Williams, R.J., 2010. The adoption of non-inversion tillage systems in the United Kingdom and the agronomic impact on soil, crops and the environment—A review. Soil & Tillage Research 108, 1–15

Nieto, O.M., Castro, J., Fernandez-Ondono, E., 2013. Conventional tillage versus cover crops in relation to carbon fixation in Mediterranean olive cultivation. Plant and Soil 365, 321–335

Ogle, S., Breidt, F., Paustian, K., 2005. Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. Biogeochemistry 72(1), 87–121

Pan, G., Xu, X., Smith, P., Pan, W., Lal, R., 2010. An increase in topsoil SOC stock of China's croplands between 1985 and 2006 revealed by soil monitoring. Agriculture, Ecosystems & Environment. 136, 133–138

Parton, W.J. and Rasmussen, P.E., 1994. Long-term effects of crop management in wheat-fallow: II. CENTURY model simulations. Soil Science Society of America Journal 58, 530–536, 1994.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G., Smith, P., 2016. Climate-smart soils. Nature 532, 49–57. doi:10.1038/nature17174.

Paustian, K., Collins, H.P., Paul, E.A., 1997. Management controls on soil carbon P. In: Paul, E.A., Paustian, K., Elliott, E.T., Cole, C.V., (Eds) Soil organic matter in temperate agroecosystems. CRC Press, Boca Raton, pp 15–49

Pituello, C., Polese, R., Morari, F., Berti, A. 2016. Outcomes from a long-term study on crop residue effects on plant yield and nitrogen use efficiency in contrasting soils. European Journal of Agronomy 77, 179–187

Poeplau, C., Don, A., 2015. Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. Agriculture, Ecosystems & Environment 200, 33–41

Pordesimo, L.O., Edens, W.C., Sokhansanj, S., 2004. Distribution of aboveground biomass in corn stover. Biomass & Bioenergy 26, 337–343

Powlson, D.S., Riche, A.B., Coleman, K., Glendining, M.J., Whitmore, A.P., 2008. Carbon sequestration in European soils through straw incorporation: Limitations and alternatives. Waste Management 28, 741–746

Powlson, D.S., Bhogal, A., Chambers, B.J., Coleman, K., Macdonald, A.J., Goulding, K.W.T., Whitmore, A.P. 2012. The potential to increase soil carbon stocks through reduced tillage or organic material additions in England and Wales: A case study. Agriculture, Ecosystems & Environment 146, 23–33

Powlson, D.S., Stirling, C.M., Jat, M.L., Gerad, B.G., Palm, C.A., Sanchez, P.A., Cassman, K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. Nature Climate Change 4, 678–683

Prager, K., Posthumus, H., 2010. Socio-economic factors influencing farmers' adoption of soil conservation practices in Europe. In: Napier, T.L. (Ed.), Human Dimensions of Soil and Water Conservation: A Global Perspective. Nova Science Publishers, Inc., New York, pp. 203–223.

Preissel, S., Reckling, M., Schläfke, N., Zander, P., 2015. Magnitude and farm-economic value of grain legume pre-crop benefits in Europe: A review. Field Crops Research 175, 64–79

Pratt, M.R., Tyner, W.E., Muth Jr., D.J., Kladivko, E.J., 2014. Synergies Between Cover Crops and Corn Stover Removal. Agricultural Systems 130, 67–76

Reckling, M., Bergkvist, G., Watson, C.A., Stoddard, F.L., Zander,P.M., Walker, R.L., Pristeri, A., Toncea, I. and Bachinger, J., 2016. Trade-offs between economic and environmental impacts of introducing legumes into cropping systems. Frontiers in Plant Science, 7:669

Rickson, J., Deeks, L., Posthumus, H., Quinton, J., 2010. To review the overall costs and benefits of soil erosion measures and to identify cost-effective mitigation measures, Sub-Project C of Defra Project SP1601: Soil Functions, Quality and Degradation – Studies in Support of the Implementation of Soil Policy

Riley H., 2016. Residual value of inorganic fertilizer and farmyard manure for crop yields and soil fertility after long-term use on a loam soil in Norway. Nutrient Cycling in Agroecosystems 104, 25–37

Robinson, D.A., Hockley, N., Cooper, D.M., Emmett, B.A., Keith, A.M., Lebron, I., Reynolds, B., Tipping, E., Tye, A.M., Watts, C.W., Whalley, W.R., Black, H.I.J., Warren, G.P., Robinson, J.S., 2013. Natural capital and ecosystem services, developing an appropriate soils framework as a basis for valuation. Soil Biology and Biochemistry 57, 1023–1033

SAC, 2013. The Farm Management Handbook 2013/14 34th Edition, SAC Consulting Ltd

Sánchez, B., Iglesias, A., McVittie, A., Alvaro-Fuentes, J., Ingram, J., Mills, J., Lesschen, J.P., Kuikman, P., 2016a. Management of agricultural soils for greenhouse gas mitigation: Learning from a case study in NE Spain. Journal of Environmental Management 170, 37–49

Sánchez, B., Álvaro-Fuentes, J., Cunningham, R., Iglesias, A., 2016b. Towards mitigation of greenhouse gases by small changes in farming practices: understanding local barriers in Spain. Mitigation and Adaptation Strategies for Global Change 21, 995-1028Scottish Government, 2005. Farm Soil Plan. Protecting soils and income in Scotland. http://www.gov.scot/Publications/2005/12/01130314/03142 (accessed 12 June 2016).

Scottish Government, 2013. 2012 methodology and quality note for Farm Accounts Survey. http://www.gov.scot/Topics/Statistics/Browse/Agriculture-Fisheries/Publications/FASmethod/FASmethod2012 (accessed 7 October 2016).

Shrestha, S. K., 2004. Adaptation strategies for dairy farms in central and north-west England under climate change. PhD thesis. University of Nottingham.

Shrestha, S., Vosough Ahmadi, B., Thomson, S., Barnes, A., 2014. An assessment of the post 2015 CAP reforms: winners and losers in Scottish farming. 88th Annual Conference, 9-11 April, 2014, Paris, France

Smith, P., Powlson, D.S., Glendining, M.J., Smith, J.U., 1997. Potential for carbon sequestration in European soils: preliminary estimates for five scenarios using results from long-term experiments. Global Change Biology 3, 67–79

Smith, P., Powlson, D.S., Glendining, M.J., Smith, J.U., 1998. Preliminary estimates of the potential for carbon mitigation in European soils through no-till farming. Global Change Biology 4, 679–685

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., 2007a. Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture. Agriculture, Ecosystems & Environment 118, 6–28

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Rose, S., Schneider, U., Towprayoon, S. & Wattenbach, M. 2007b. Agriculture. In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A., (Eds), Contribution of Working group Climate Change 2007: Mitigation of Climate Change: Working Group III contribution to the Fourth Assessment Report of the IPCC. Cambridge University Press, Cambridge, United Kingdom

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H.H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, R.J., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J.U., 2008.

Greenhouse gas mitigation in agriculture. Philosophical Transactions of the Royal Society B 363, 789–813

Snyder, C.S., Bruulsema, T.W., Jensen, T.L., Fixen, P.E., 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agriculture, Ecosystems & Environment 133, 247–266

Soane, B.D., Ball, B.C., Arvidsson, J., Basch, G., Moreno, F., Roger-Estrade, J., 2012. No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. Soil & Tillage Research 118, 66–87

Steenwerth, K., Belina, K.M., 2008. Cover crops enhance soil organic matter, carbon dynamics and microbial function in a vineyard agroecosystem. Applied Soil Ecology 40, 359–369

St. Luce, M., Grant, C.A., Ziadi, N., Zebarth, B.J., O'Donovan, J.T., Blackshaw, R.E., Harker, K.N., Johnson, E.N., Gan, Y., Lafond, G.P., May, W.E., Malhi, S.S., Turkington, T.K., Lupwayi, N.Z., McLaren, D.L., 2016. Preceding crops and nitrogen fertilization influence soil nitrogen cycling in no-till canola and wheat cropping systems. Field Crops Research 191, 20–32

Sun, B., Hallett, P.D., Caul, S., Daniell, T.J., Hopkins, D.W., 2010. Distribution of soil carbon and microbial biomass in arable soils different tillage regimes. Plant and Soil 338, 17–25

Taghizadeh-Toosi, A. & Olesen, J.E., 2016 Modelling soil organic carbon in Danish agricultural soils suggests low potential for future carbon sequestration. Agricultural Systems 145, 83-89

Townsend, T., Ramsden, S., Wilson, P. 2016a. How do we cultivate in England? Tillage practices in crop production systems. Soil Use and Management 32, 106–117

Townsend, T.J., Ramsden, S.J., Wilson, P., 2016b. Analysing reduced tillage practices within a bio-economic modelling framework. Agricultural Systems 146, 91–102

Troccoli, A., Maddaluno, C., Mucci, M., Russo, M., Rinaldi, M. 2015. Is it appropriate to support the farmers for adopting conservation agriculture? Economic and environmental impact assessment. Italian Journal of Agronomy 10, 169–177

Urbano, P., 2002. Fitotecnia. Ingenería de la producci_on vegetal. Mundi-Prensa, Madrid, Spain.

Van Alphen, B.J., Stoorvogel, J.J., 2000. A methodology for precision nitrogen fertilization in high-input farming systems. Precision Agriculture 2, 319–332

West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. Soil Science Society of America Journal 66, 1930–1946

Whitmore, A., Kirk, G., Rawlins., B. 2015. Technologies for increasing carbon storage in soil to mitigate climate change. Soil Use and Management 31, 62–71

Williams, A., Hunter, M.C., Kammerer, M., Kane, D.A., Jordan, N.R., Mortensen, D.A., Smith, R.G., Snapp, S.S., Davis, A.S., 2016. Soil water holding capacity mitigates maize production downside risk and volatility in US rainfed maize: Time to invest in soil organic matter? PLOS ONE 11, (art. 0160974)

Wösten, H., Kuikman, P., 2014. Deliverable D1.3: Report describing the practices and measures in European farming systems to manage soil organic matter. Report for EU FP7 SmartSOIL (Grant Agreement N° 289694). Available at http://smartsoil.eu/

Zibilske L.M., Bradford, J.M., 2007. Soil aggregation, aggregate carbon and nitrogen, and moisture retention induced by conservation tillage. Soil Science Society of America Journal 71(3), 793–802

Supplementary material

Table S1. Sensitivity analysis of the SOC scenarios farms in Scotland, UK (corresponding figure: Figure 4)

Scenarios	Farm types	Sensitivity analysis cases											
		YmaxCmax			YmaxCmin			YminCmax			YminCmin		
		2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025
CCLeg	**Large**	-0.017	-0.017	-0.016	0.057	0.060	0.059	-0.030	-0.030	-0.030	-0.004	-0.004	-0.004
	Medium	-0.024	-0.024	-0.023	0.070	0.071	0.070	-0.062	-0.062	-0.062	-0.009	-0.009	-0.009
	Small	-0.024	-0.024	-0.024	0.074	0.075	0.074	-0.066	-0.066	-0.066	-0.011	-0.012	-0.012
CCNoLeg	**Large**	-0.014	-0.014	-0.014	0.019	0.019	0.018	-0.025	-0.025	-0.025	-0.006	-0.006	-0.006
	Medium	-0.024	-0.024	-0.024	0.029	0.029	0.028	-0.055	-0.055	-0.055	-0.016	-0.016	-0.016
	Small	-0.026	-0.026	-0.025	0.029	0.029	0.028	-0.059	-0.060	-0.059	-0.019	-0.019	-0.019
ZeroTill	**Large**	0.037	0.060	0.075	0.097	0.126	0.142	-0.155	-0.106	-0.076	-0.109	-0.054	-0.021
	Medium	0.039	0.061	0.075	0.092	0.120	0.135	-0.142	-0.097	-0.068	-0.102	-0.049	-0.018
	Small	0.038	0.060	0.075	0.092	0.120	0.136	-0.147	-0.100	-0.071	-0.106	-0.053	-0.021
RedTill	**Large**	0.092	0.091	0.091	0.126	0.127	0.127	-0.064	-0.063	-0.063	-0.036	-0.033	-0.033
	Medium	0.086	0.084	0.084	0.120	0.121	0.120	-0.061	-0.060	-0.060	-0.033	-0.030	-0.030
	Small	0.085	0.084	0.084	0.120	0.121	0.120	-0.064	-0.064	-0.064	-0.036	-0.033	-0.033
ResMan	**Large**	-0.104	-0.054	-0.101	0.062	0.068	0.068	-0.225	-0.220	-0.220	-0.089	-0.082	-0.082
	Medium	-0.104	-0.056	-0.103	0.056	0.062	0.062	-0.216	-0.213	-0.213	-0.085	-0.078	-0.078
	Small	-0.105	-0.060	-0.104	0.055	0.061	0.061	-0.220	-0.218	-0.217	-0.089	-0.082	-0.082

Table S2. Sensitivity analysis of the SOC scenarios for farms in Aragon, Spain (corresponding figure: Figure 6)

Scenarios	Sensitivity analysis cases											
	YmaxCmax			YmaxCmin			YminCmax			YminCmin		
	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025
CCLeg	0.035	0.035	0.035	0.064	0.064	0.064	-0.142	-0.141	-0.141	-0.045	-0.045	-0.045
CCNoLeg	-0.017	-0.017	-0.017	0.049	0.049	0.049	-0.088	-0.087	-0.087	-0.031	-0.031	-0.031
RedTill	-0.165	0.024	0.151	-0.146	0.056	0.187	-0.341	-0.171	-0.058	-0.326	-0.146	-0.029
ResMan	-0.064	-0.063	-0.063	-0.029	-0.025	-0.025	-0.043	-0.042	-0.042	-0.042	-0.039	-0.039
FertMan	0.270	0.268	0.268	0.309	0.307	0.307	0.034	0.034	0.034	0.065	0.064	0.064
OptFert	0.312	0.309	0.309	0.320	0.326	0.325	-0.272	-0.271	-0.271	-0.268	-0.262	-0.262
CRot	0.422	0.424	0.423	0.427	0.437	0.437	0.168	0.170	0.170	0.171	0.179	0.179